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ADAPTIVE LOCOMOTION ON VARYING GROUND CONDITIONS VIA A RECONFIGURABLE LEG LENGTH HOPPER

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In this paper, we present the concept of adapting to changes in ground conditions like stiffness, damping and friction, using a novel two degree of freedom reconfigurable leg length hopping robot with a fixed passive compliance. In such a robot, the change in the dynamics of the single legged hopper can be induced by the change in coupled stiffness and damping of the system, i.e., stiffness and damping of the ground coupled with the stiffness and damping of the robotic leg. It is experimentally shown by in-place hopping of a robotic leg on various grounds (stiff, less stiff and soft) that the leg can effectively adapt to changes in coupled stiffness and damping by the rate and the amplitude at which the leg length changes. This is true, while the leg hops in-place as the role of ground friction is negligible. However, in forward motion where the ground friction dominates, a change in initial effective leg length, i.e., shortening or lengthening can provide an additional support to the hip motor in overcoming even large variations in ground friction. This is demonstrated through a planar locomotion experiment on different ground surfaces. The overall results provide strong support for this concept.

Keywords: Varying ground conditions, changeable leg length.

1. Introduction

Animals and humans are capable to adapt to varying ground conditions (stiffness, damping and friction) while maintaining their balance on irregular surfaces [1]. This kind of adaptive behaviour is a great source of inspiration for designing legged robots. In general, ground surfaces can be characterized by their stiffness, damping and friction properties. In legged robot locomotion, one approach to adapting to varying ground conditions is by physically changing parameters of the robotic leg to counter-act the overall change. For example, in [2] mechanically adjustable compliance in the robotic leg was introduced to adapt to the change in stiffness of the underlying surface. However, it is not entirely clear how these changes can be incorporated in practice during fast running of a legged robot. Except for the pioneering work of Marc Raibert [1], most of the electrically actuated legged robots developed in the past were designed to exploit the potential of passive compliance [3], [4], together with the

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oscillatory motion of the robotic leg. However, due to exploiting limited degrees of freedom in [3], [4], the performances of these systems were mainly restricted to stiff grounds. In this study, we demonstrate that, in the context of adaptive legged robot locomotion, all three ground properties, namely stiffness, friction and damping, are equally important. In other words, efficient adaptation should consider all three ground conditions in a unified framework.

We developed a bio-inspired 2-DOF robotic leg whose design of [5] follows the spring loaded inverted pendulum (SLIP) model, also referred to as the bouncing motion [5]. In [5], the altering leg length feature was first introduced. In this paper, we propose a systematic approach, which is based on the concept of embodiment [6], in order to test the framework of [7] for varying ground conditions. According to [6], the dynamic coupling of the robot's body with its controls and the physical environment is important to investigate the overall behavior of the robot. By employing this concept, the effects of altering leg length are practically investigated on number of different grounds. Experimental results demonstrate that the reconfigurable leg length approach is suitable to efficiently adapt to varying ground conditions both for in-place and planar hopping.

The remainder of this paper is structured as follows: Section 2 describes the mechanical structure and the control of the robotic leg. Section 3 explains the proposed mathematical model. Experiments and results are provided and discussed in Section 4. Finally, Section 5 draws some conclusions and details the future research direction of this work.

2. Mechanical Design and Control

The 2-DOF reconfigurable leg length hopper (RLLH) module, as shown in Fig. 1, was designed and constructed based on the SLIP model [7].

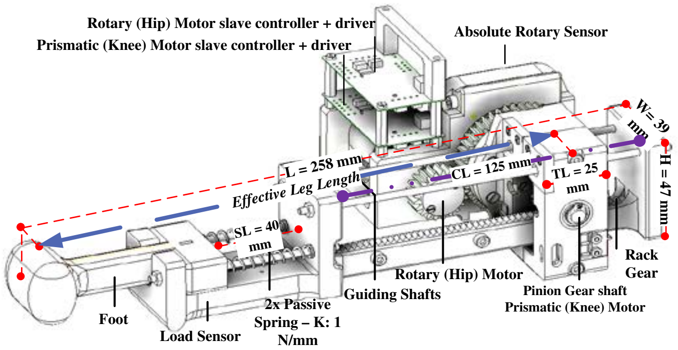

Figure 1. Reconfigurable Leg Length Hopper (RLLH) module. Leg segment dimension *(LxWxH: 258x39x47 mm^3)*; total weight (including the weight of the boom rod, which can be seen in Fig. 4 (a): *0.778 ± 0.001 kg*. Purple line shows the range of reconfigurable leg length (CL). Blue line indicates the effective leg length (i.e., It is a distance measured from the center of rotation to the ground).

However, in contrast to the standard SLIP model, the leg has an additional active DOF, i.e., a linear joint which works in series with the passive compliance, similar to a muscle-tendon mechanism in a biological system [8]. This additional DOF provides supplementary advantages over the SLIP model, i.e., it regulates the energy into the passive-spring by altering the amplitude and the rate at which the leg length changes. In addition, adjusting the initial leg length to the various settings, i.e., shifting the initial set position of the leg in order to make it shorter or longer, can now be achieved online. In order to make the design lighter, two electric DC brushed motors are used. The first DC motor drives the linear motion for changing the leg length while the second one allows for a rotary motion of the hip joint.

The control of the RLLH [7] consists of a two layer framework. At the lower level, two types of positional PID motor control loops, one each for the rotary and the linear motion, were implemented. The gains of each PID were experimentally tuned for good performance. On the higher level, an open-loop sinusoidal control scheme was programmed in a master controller. It computes the desired trajectory of each joint by processing control functions (see section 2.2) at the rate of *125 ± 2.4E-05 Hz.* The results from this computation are then transmitted to the low level PID control for the execution of joint motion.

2.1. *Control law*

The oscillator force F_m, due to the motion of the reconfigurable linear joint, for a given operating time t is defined as follow:

$$F_m = -\frac{I_l}{d^2}\left(\Delta l {\omega^2}_p\right)\sin\left(\omega_p t + \varphi_p\right), \tag{1}$$

where, I_l is the moment of inertia of the leg, d is the radius of the pinion gear, Δl is the change in leg length (amplitude), $\omega_p = 2\pi f_p$ is the angular frequency of the oscillator, and φ_p is the phase shift in the oscillator. Furthermore, $v_p = \omega_p * d$ and $\Delta l = v_p * t$. F_m acts such that, when the leg length increases during the first phase of the control signal, the body moves up consequently performing positive work at the passive spring. This work is done by pushing the leg against the ground thus storing some energy in the spring. During the next phase of the control signal, when the applied torque is in the counter-clockwise direction, the leg length reduces by effectively taking the energy from the system (the negative work). Hence, by applying a simplified oscillatory control signal of various amplitudes and frequencies, the required energy in the passive spring can be regulated.

Similarly, the torque τ_r produced by the rotary joint during the oscillatory motion in the sagittal plane, is defined as

$$\tau_r = I_l * \ddot{\theta}_r = -\Delta\theta_r \omega_r^2 \sin(\omega_r t + \varphi_r), \tag{2}$$

where, $\ddot{\theta_r}$ is the joint angular acceleration, $\Delta\theta_r$ is the amplitude of the rotary motion, ω_r is the angular frequency of the oscillator, and φ_r is the phase offset of the oscillations. By adjusting the parameters $\Delta\theta_r$, ω_r and φ_r in the above equation, the forward and backward motion of the leg is controlled.

3. Mathematical Model

The dynamics of the in-place hopping of the RLLH can be described by the mass-spring-damper model, as shown in Fig. 2. By conducting a force analysis of the model, a differential equation describing the motion of the center of mass of the robotic leg, when the ground stiffness is high, is obtained as,

$$m\ddot{y} + D_l\dot{y} + k_l y = F_m + mg, \qquad (3)$$

where, y is the motion of the body in the vertical axis, D_l is the damping while k_l is the stiffness constant of the leg, F_m is the oscillatory force produced by the motion of the prismatic joint, as defined in (1), and $m.g$ is the weight of the module. According to (3), when the ground surface is highly stiff, the natural frequency of the system can be defined as,

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_l}{m}}, \qquad (4)$$

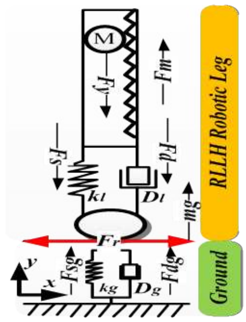

Figure 2. A mass-spring-damper representation of the robotic leg during in-place hopping.

However, for varying ground conditions, the resulting natural frequency f_0 of the system is not only a function of the stiffness and the damping of the robotic leg but it becomes a function of the coupled properties of the two, i.e., stiffness and damping of the ground coupled with the stiffness and damping of the robotic leg (see Fig.2, a model of RLLH (orange) in connection with the model of the ground (green)). These coupled properties affect the overall system dynamics when the leg is in contact with the varying ground conditions. In this case, the coupled stiffness k_c is defined as,

$$k_c = \frac{k_l * k_g}{k_l + k_g}, \qquad (5)$$

where, k_l is the leg stiffness and k_g is the ground stiffness. The resulting natural frequency of this coupled interaction can be represented as,

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k_c}{m}}, \qquad (6)$$

In case of very stiff grounds, i.e., $k_g \gg k_l$, the natural frequency of the system (6) mainly depends on k_l, because the coupled stiffness k_c reduces to k_l.

On the other hand, when the ground is soft, i.e., $k_g \ll k_l$, the ground stiffness dominates the system behavior and the coupled stiffness k_c reduces to the ground stiffness k_g. Thus, in this case k_g defines the natural frequency of the coupled system. Since, for soft grounds, k_g is lower than that of k_l, the required operating frequency of the actuator in order to adapt to surface changes will also be lower than in the case of stiff ground. This is advantageous, since, the electric actuators such as the DC brushed motors typically have a limited operational bandwidth. At the lower operating frequency, such motors can potentially be more efficient.

The presence of the dissipative forces, such as friction is very common in real systems. It causes a decrease in mechanical energy during the motion. This effect is modeled as a damper in our system that depends on the speed of the body. In a coupled system, its effect will be additive and can be compensated by injecting more energy (see Equation 1).

These two ground properties (stiffness and damping) lead to a change in the natural frequency and the amplitude of the power consumption of the system for varying grounds, which is shown in number of experiments (see Section 4.1).

The ground friction comes into play during the forward motion of the robotic leg. Due to varying nature of the ground, friction also varies and one way to compensate this change in friction is to reduce the length of the leg such that the rotary joint requires less torque to efficiently negotiate with the ground friction. This relation of the rotary joint torque τ_r and the leg length is defined as

$$\tau_r = F_r * \{L_0 + \Delta l \sin(\omega_p t + \varphi_p)\}, \quad (7)$$

where, L_0(initial leg length), Δl (change in leg length), and ω_p (rate of change). Thus, the shorter leg can theoretically negotiate better both the high and the low friction grounds compared to the longer leg. However, a longer leg can be useful in situations where an increased locomotion speed is required. The latter can be achieved by increasing the leg length during the steady state locomotion when the effect of the static friction becomes smaller. This is experimentally verified in section 4.2.

4. Experiments and Results

To test the role of the reconfigurable leg length for different ground conditions, two types of dynamic motions of the RLLH were studied: one, when the leg hops in-place on various grounds (see Section 4.1) and second, when the leg ran in hopping gait over different grounds, while being fixed to a boom (see Section 4.2).

4.1. *Hopping In-Place*

This experiment was conducted while the robot was in an upright posture with respect to the ground. Hopping was achieved by actuating the hip motor at a constant position (i.e., the hip angle is fixed at *π/2 rad*). In-place hopping was performed by varying two parameters, the amplitude (Δl) and the frequency (f_p) in equation (1) that controls the force produced by the prismatic motion. For each change in amplitude and frequency, the total electrical power consumption of the RLLH was measured. The same experiment was repeated on three types of ground surfaces: stiff (force plate), less stiff (gym training mat) and soft (foam), as shown in Fig. 3 (a). In total, *152* combinations including *4* different amplitudes *(4-28 mm in steps of 8 mm)* and *38* different frequencies *(0.5-10 Hz in steps of 0.25 Hz)* were experimentally tested per ground surface.

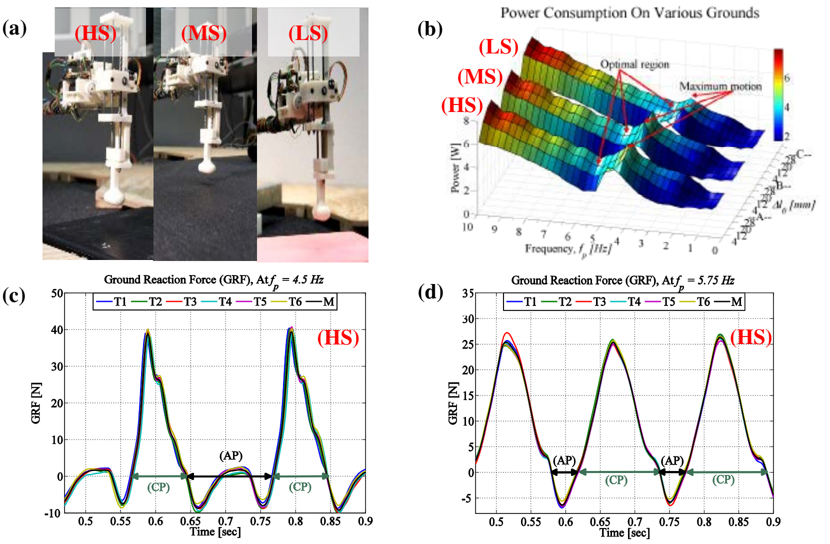

Figure 3. Hopping in place experiments. **(a)** Photographs taken during the experiment over (HS) very stiff ground (force plate), (MS) medium stiff ground (gym training mat), and (LS) soft, low-stiff ground (foam). **(b)** The power consumption plot for HS, MS, and LS. The x-axis represents the frequency ranging from *(0.5-10Hz in steps of 0.25Hz)*, the y-axis the amplitude of change in leg length *(4-12-20-28mm)* relative to the initial effective leg length of *135.5mm*, and the z-axis represents the electrical power consumption averaged over *6 trials* per control parameter. The duration of each trial was *7 sec*. **(c)** The ground reaction force (GRF) measured at a forced frequency (f_p) of *4.5 Hz* on ground (HS). At this frequency the robotic leg achieved the maximum aerial phase (AP) – see the duration of contact phase (CP) and aerial phase (AP) in Fig. 3 (c). This reflects the increase in the ground impact, thus the power consumption- see Fig. 3 (b), (HS). **(d)** The GRF measured at the optimal forced frequency *5.75 Hz* on ground (HS), where the lowest power consumption was observed. At this point the aerial phase decreases to the value shown in Fig. 3 (c). These results from c) and d) also indicate that the duration of the contact phase (CP) and the aerial phase (AP), can be actively modulated by the rate of change in leg length to adapt to varying ground conditions. As we formulated in (5) that on stiff ground such as (HS), the coupled stiffness k_c reduces to the leg stiffness, i.e. $k_c = k_l = 1\ N/mm$ – see Fig. 1. By substituting this value of k_l and *m: 0.778* ± *1E-3* k_g in equation (5), the natural frequency f_0 is computed, which yields *5.70 Hz*. This theoretical f_0 approximately matches the optimal frequency of (HS), which is *5.75 Hz,* where the robotic leg is energy efficient in maintaining steady-state hops.

It can be observed in the respective plot that the power consumption over different grounds (HS), (MS), and (LS) follows nearly the same pattern. On each of these surfaces, the power consumption is low at lower frequencies and it increases proportionally with the frequency. Interestingly, a sharp peak in the power curve is observed just after the frequency, where the in-place hopping started (see Fig. 3 (b), (HS) it is *4.25 Hz*). This peak represents the point where the contact phase (duration on ground) is less than the aerial phase (duration in air), i.e., high ground clearance, as can also be seen in Fig. 3 (c). Right after that, the power consumption sharply drops again as the frequency increases further and the contact phase (CP) increases compared to the aerial phase (AP) (see Fig.3 (d)). This frequency is the optimal frequency of the coupled system as it consumes least power. By further increasing the frequency above the optimal frequency, the power consumption increases too due to the decrease in aerial phase (AP). This shows that by altering the rate of change in leg length caused by the change in the frequency (f_P) of the actuation control signal in equation (1), the passive spring can be actively tuned to work in two different modes: First, in the energy efficient mode (optimal region), where the system can consume the least power and, second, an energy inefficient mode (maximum motion), where the system consumes more power but achieves high ground clearance. These modes are essential in designing the optimal control by exploiting the use of the passive compliance for locomotion.

As can be observed further, the optimal frequency for the soft ground (LS) shifted to a lower frequency as compared to the stiffer grounds (HS) and (MS). This shift in the frequency of overall system was caused by the change in the coupled stiffness and damping properties of the robotic leg with the ground surface, as formulated in equation (6). However, the proposed design is potentially able to adapt to it by varying the rate of change in leg length (see in Fig. 3 (a) In addition, it was observed that to efficiently adapt to the soft ground by mitigating the effect of deformation, higher ground clearance will also be needed. This can be obtained by increasing the amount of change in leg length at the optimal frequency.

4.2. *Planar Locomotion in a Hopping Gait*

This experiment was performed by operating both the rotary (at the hip) and prismatic motors (to change the leg length) at the frequency of *5 Hz*, which has been previously obtained from the in-place hopping experiment (see Fig. 3). For the planar locomotion, the amplitude of the oscillation of rotary hip joint was kept constant at *0.1745* ± *0.035 rad*. In addition, the phase shift between the rotary and the prismatic actuation signals was set to *0.92* rad with the change in leg length (i.e., Δl_0) to *10 mm and 18 mm*, during all trials. Only the initial effective leg length was altered (see Fig. 1), thereby the initial distance between the hip and the ground was changed (i.e., simulating different heights of the leg). In each trial, the angular velocity ω_s (see Fig. 4 (a)) about the boom fixed coordinate system was measured using the gyro and it was then converted into planar velocity.

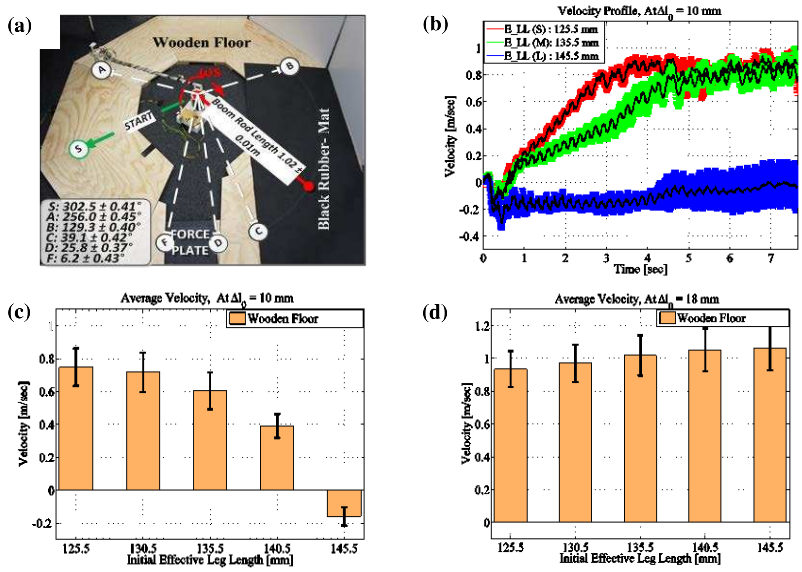

Figure 4. Forward hopping experiment. **(a)** A top view of the experimental-setup. Each trial ends after completing one revolution about the fixed boom axis. **(b)** The velocity profile with respect to the different initial leg lengths *(125.5 (short), 135.5(medium) and 145.5(long) in mm)*. For each leg length settings 5 trails were performed; the shaded region indicates the error about the mean value. **(c)** The measures of the change in forward velocity on wooden grounds with respect to the different initial leg settings. **(d)** The measures of change in forward velocity on wooden ground, when the amplitude of change in leg length Δl_0 increases to *18mm* than Fig. 4 (c).

As shown in Fig. 4 (b) and (c), the velocity at the smaller leg length (red curve) increases faster to the maximum than to the medium (green) and longer leg length (blue). Since the starting point for all these experiments were on wooden floor, we showed that the robotic leg in the short leg configuration was able to recover faster from the static-friction, than in the larger leg length condition, as described by equation (7). However, when the amplitude of change in leg length increases to 18 mm than 10 mm, then it enables the robotic leg to recover faster from the effect of friction, maintaining an increase in overall average locomotion speed with respect to increase in leg length, as shown Fig. 4 (d).

5. Conclusion and Future Work

We have practically demonstrated, that the reconfigurable second DOF of the RLLH that works in series with the passive compliance, is potentially useful to adapt to the changes in ground conditions like stiffness, damping and friction. It can be simply achieved by adapting the amplitude of the linear leg movement and its rate of change in the leg length. Both changes can be rapidly applied to compensate for the change in the overall system behavior, i.e., the change in coupled stiffness and damping between leg and ground. In addition, shortening and lengthening the leg makes this design equally suitable for compensating the varying ground friction. Moreover, the speed of the locomotion, which also depends on the leg length, is also controllable. Furthermore, we highlighted in the in-place hopping experiments that our robotic leg can function in two modes, the optimal energy efficient mode *(aerial phase < contact phase)* and the high bounce energy in-efficient *(aerial phase > contact phase)* mode.

In the near future, these results will be incorporated in a closed loop control for the RLLH. Similar concept will be extended towards controlling a state of the art robot called DTAR that consists of 4 of the presented robotic legs (RLLH).

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